Test Philosophies for the New Millennium

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Abstract

Current economic and political trends are producing a new environment within NASA, resulting in an emphasis on "faster, better and cheaper" space missions in lieu of the large, high cost projects of years past. In this new environment JPL will retain its fundamental role of robotic space exploration, but will implement this role using relatively small, inexpensive and rapidly developed spacecraft. Hardware for these new vehicles will rarely be built in-house, but will instead be procured through partnerships with both industry and academia.

Clearly this change in mission scope, philosophy and size will require new strategies and techniques for environmental testing. Early involvement with partners will be essential, so that unnecessary, redundant or unrealistic tests can be omitted from the outset, and those activities most effective in mitigating risk can be retained. The multi-year test program of the past, utilizing repeated trials at several levels of assembly, must now be replaced with a streamlined plan balancing cost, schedule and risk.

Current research at JPL is directed toward the optimization of future spacecraft testing. Force-limited vibration studies, conducted during several recent space vehicle programs, have been extremely successful in improving the quality and realism of hardware trials. Single versus triaxial vibration research is also in progress, with a similar objective of test realism enhancement. In addition, use of the Environmental Test Effectiveness Assessment (ETEA) process has helped to identify those tests which most effectively isolate hardware defects.

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The research described in this paper was carried out at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

TEST PHILOSOPHIES FOR THE NEW MILLENNIUM

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Keywords

VIBRATION, ENVIRONMENTAL TEST, FORCE LIMITING, 2-SIGMA ENVELOPE, ACEQ

Abstract

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Introduction

The current political and socio-economic environment in the U.S. has provided a mandate for change in virtually every aspect of government, with public-funded scientific endeavors, including space exploration, notwithstanding,. NASA has responded to this mandate with the goal of a faster, better and cheaper space mission, where costs are minimized, program objectives are reduced in scope but nonetheless aggressive, and schedules are compressed as tightly as possible.

To become "faster" and "better", future projects will require JPL and other sites to focus far less on in-house hardware development, and far more on contract procurement via partnerships with both industry and academia. The rationale behind such a strategy is to make the most efficient use possible of recognized experts, be they propulsion component manufacturers in private industry or robotics researchers at MIT. Within such a strategy, JPL will ultimately become a systems integrator, charged with managing external technology development such that space mission objectives are accomplished.

While "old-style" large spacecraft programs such as Galileo and Cassini had total costs in excess of 1 billion dollars and a complex science payload, more recent projects such as Mars Global Surveyor and the New Millennium program have cost caps under $100 million. The lower cost is necessarily accompanied by smaller size and shorter project schedules. Whereas past environmental testing was comprehensive and conservative, the new project environments demand a careful examination of environmental test programs to maximize test budget effectiveness.

To this end, the Jet Propulsion Laboratory has undertaken various studies to determine the effectiveness of available environmental tests, and to thereby develop information the project can use within it's overall risk management decisions. This paper will discuss environmental testing philosophy at JPL, environmental test studies performed to date, results of the 2 sigma launch vehicle dynamics environment study, development of the Advanced Cost Effective Qualification (ACEQ) methodology and, finally, current studies targeting New Millennium product assurance.

JPL Environmental Test Philosophy

The environmental test philosophy at JPL has traditionally been very conservative and rigorous. With the advent of each new flight project a new test program, specifically tailored for the mission in question, was developed. Testing would initially commence at the assembly (e.g. electronic box) level, continue further at the subsystem level, and ultimately apply to the integrated spacecraft. Tests performed included sine, random vibration, pyroshock, thermal vacuum, conducted and radiated emissions and susceptibility. These tests were performed in addition to a plethora of developmental, trouble shooting, checkout, functional and acceptance tests which would be conducted either by a responsible in-

Table 1- Typical Spacecraft Test Program

Environment	Assembly	Subsystem	Spacecraft
Sine Vibration	Not Required	Required	Required
Random Vibration	Required	Required	Required
Acoustic	Not Required	Not Required	Required
Pyro Shock	Required	Required	Required
Thermal Vacuum	Required	Required	Requi red
Thermal Shock	If Applicable	Not Required	Not Required
Conducted Suscept	Required	Required	Required
Radiated Suscept	Required	Required	Required
Conducted Emission	Required	Required	Required
Radiated Emission	Required	Required	Required
Magnetic Survey	Required	Required	Required

house engineering team, by the vendor, or both. Table 1 illustrates a typical environmental test program, reflecting prior JPL practice for the Viking, Voyager, Galileo and Cassini missions.

Such an approach is clearly thorough and comprehensive, and worked well within the context of the large spacecraft program for which it was developed. However, there is an ongoing trend toward dramatic reduction in the physical size of spacecraft, as illustrated in Figure 1.

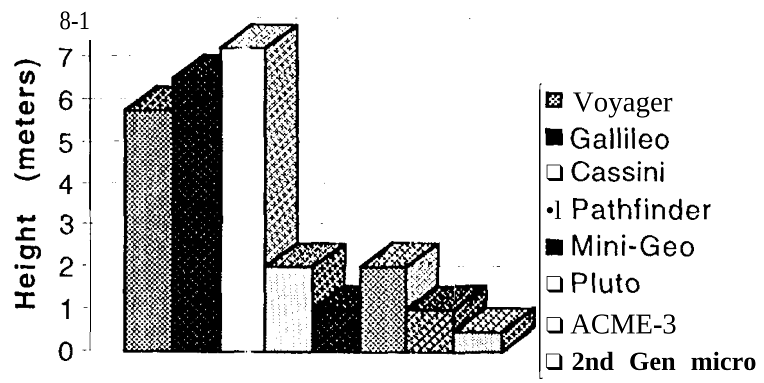

Figure 1 - 'l'rend In Physical Spacecraft Size

Along with this reduction is size has come a significant reduction 'in overall project costs, which has severely impacted the scope of environmental testing programs. Table 2 provides a comparison of total project costs and durations for a number of deep space missions, ranging from the "monster" spacecraft of years past to the plans for aggressive small missions of tomorrow.

Table 2- Project Cost Corn parison

Project	Launch Date	Duration (Years)	Cost (Millions)
Voyager	August 1977	29	$1316
Magellan	May 1989	11	$796
Galileo	October 1989	20	$1915
TOPEX	August 1992	11	$595
Mars Pathfinder	Dec. 1996	.1	$150
Cassini	October 1997	12	$1400
NMP Flight #1	January 1997	2	$50
NMP Flight #2	January 1998	3	$50?
NMP Flight #3	January 1999	4	$50?

An example of the current goals for reducing project cost and schedule, the Mars Pathfinder project has a total cost cap of $150 million, with Phases C and D lasting 3 years. The goal for future missions of this type is to achieve the same with a $100 million cost cap, and an 18 month phase C/D effort.

The small, so-called "new millennium" missions represent a change in direction for both JPL and NASA, in which many smal I spacecraft utilizing increasingly advanced technologies will be launched over a short period of time. The first of these, designated above as NMP Flight #1, will demonstrate the feasibility of solar electric propulsion in a rendezvous With a comet or an asteroid. Another NMP mission will demonstrate the use of synthetic aperture interferometry, using a three-spacecraft constellation flying in formation and linked using laser communicant ion. Another, flying as a "tag-along" on a future mission to Mars, will penetrate the Martian surface and relay physical data to the main mission spacecraft. As indicated in the table above, the cost for each of these missions will be capped at $50 million.

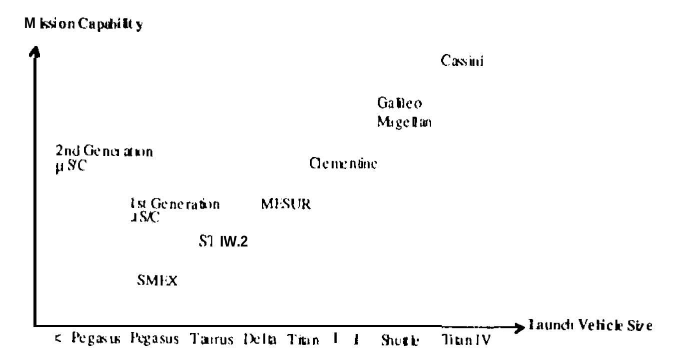

Figure 2- Microspacecraft Development

In a further push toward cost containment, JPL and other NASA sites will, in future projects, be held accountable not only for the costs of a spacecraft or flight assembly but for that of the launch vehicle as well. 'I'his reflects a radical departure from the accounting strategies of years past, and will force frugality in space missions through the emphasis of smaller, cheaper and more efficient launch platforms. Figure 2 illustrates this trend, indicating relative mission capability versus launch vehicle size for both "old school" spacecraft and micro-vehicles of the future.

In an era of such downscaling, it is critical to evaluate the purpose and objectives of the environmental test program. These objectives must be clearly defined and examined in the context of an overall space mission. The effectiveness of available tests must be assessed, and any which are found to be ineffective or irrelevant to a particular technology must be deleted or modified. Next, the consequences of test deferral to higher levels of integration must be considered. Finally, the preferred types of test to be performed at each level of assembly must be identified. such that available program funds are-optimized and costs arc held to a minimum.

Clearly these decisions must be made in conjunction with hardware contractors, and they must be made as early as possible in the project timeline. The final test program will then be tailored to both fiscal and programmatic needs, while nonetheless mitigating risk to the flight hardware.

Environmental Test Studies

Environmental test studies at JPL include research into force-limited vibration, as well as single axis versus triaxial vibration test studies. Both efforts have the goal of improving the quality and realism of hardware trials. Additionally, the Lab has performed a detailed study comparing the effectiveness of thermal cycling versus burn in of electronic assemblies, and has successfully utilized the Environmental Test Effectiveness Assessment (ETEA) process to identify tests which most effectively isolate hardware defects. Each of these topics will be discussed in turn.

Force Limited Vibration

In the force limiting approach to vibration test control, interface forces between the test article and its vibration fixture mount are monitored in real time. This information is fed back to shaker control electronics, and shaker output is subsequently corrected to prevent the interface forces from exceeding a specified limiting envelope, 'l'he envelope typically is developed from launch and flight load predictions.

The primary advantage of the force technique is that it effectively matches impedance between the test article and shaker. While a spacecraft support structure will generally have mechanical impedance similar to that of any mounted hardware, a vibration test of the same hardware will utilize a shaker having virtually infinite impedance and, as a consequence, virtually unlimited force capability. If a traditional, acceleration response based control technique is utilized in such a setup, interface forces between the test article and shaker can be excessively high during resonance. The resulting overtest can damage flight hardware, or at very best result in overly conservative structural design.

Thus, when interface forces are monitored and controlled, the resulting hardware test is more representative of an actual flight loading condition. This force limiting approach has been implemented at JPL for approximately 5 years, and has been utilized on a number of flight projects. Table 3 lists some of the flight hardware tested to date.

Table 3- JPL Force Limited Vibration Experience

Project	Test Article
MISR	Cameras
Cassini	Visual/IR Mapping Spectrometer Cooler
Cassini	Narrow_ At&Camera
Cassini	Radioisotope Thermoelectric Generators
NASA Scatterometer	Antennae
Shuttle Imaging Radar C	Electronics
Space Telescope	Wide Field Planetary Camera
TOPEX	Spacecraft Assy
Mars Observer	Camera
Mars Observer	Pressure Modulator Infrared Radiometer

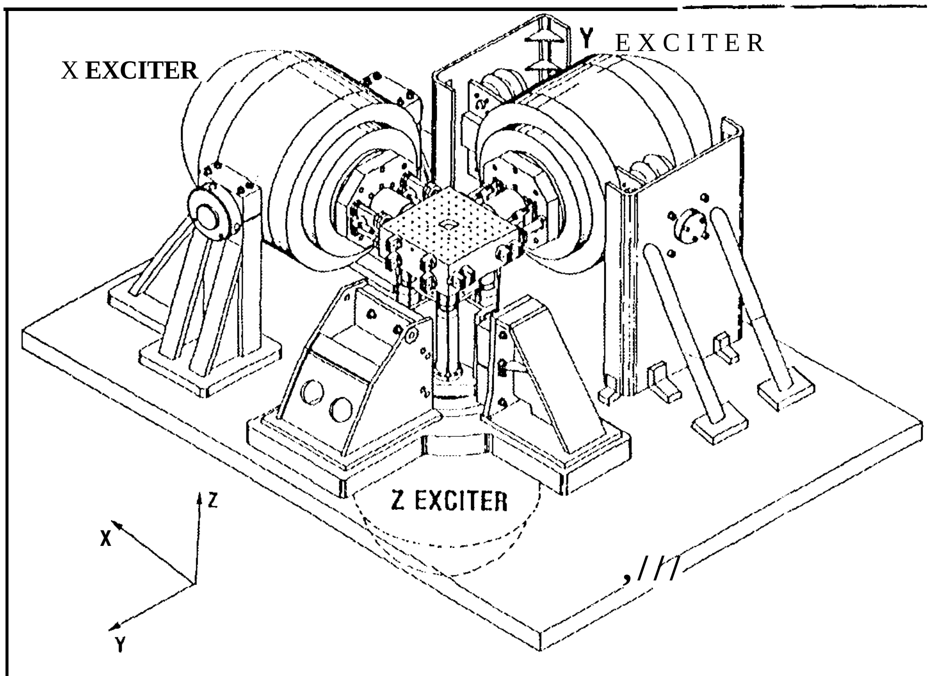

Figure 3- USARL Triaxial Vibration Test Setup

provide independent excitation in as many as three axes. The setup is illustrated in Figure 3.

Using a Miner's Rule fatigue damage accumulation method, the study found that the triaxial test induced approximately twice the damage as the three independent, single axis tests. Although many assumptions were required in reaching this conclusion, it is nonetheless significant, and calls for a re-thinking of traditional vibration test techniques, Single axis testing, while expedient and relatively cheap, may not reflect reality, and may in fact produce a significant undertest of flight hardware. When such tests are further optimized or "polished" through the use of force-limiting control techniques as described above, the mechanical input to and resulting fatigue damage accumulation in space flight equipment may be severely underrepresented.

Single versus Tri-axial Vibration

A recent research project at JPL was directed toward understanding the effects of single axis vibration versus three simultaneous axis testing. The launch environment for space flight hardware, consisting primarily of acoustic noise and structurally transmitted random vibration, is clearly input to vehicle mounted hardware in all axes at the same time. It is traditional industry practice, however, to conduct random vibration tests independently, one axis at a time. The reasons for this practice stem largely from the inaccessibility and high cost of multiaxial shaker setups.

The JPL study attempted to compare the cumulative fatigue damage induced on a typical piece of flight hardware in a one-minute triaxial test with that induced during three one-minute uniaxial tests. The input random vibration spectrum utilized in the survey was the MIL-STD-1 540 minimum integrity level for acceptance, with a peak power spectral density of .04 g^2/Hz. The applied spectrum is illustrated in Figure 4.

Testing for the study was conducted at the U.S. Army Research Laboratory in Adelphi, Maryland, using a special arrangement of three Ling Dynamics electrodynamic shakers, mechanically linked to

Thermal Testing Study

The thermal testing study [3] compared the widely accepted testing practice of thermal cycling with a dwell or 'burn in' test. It has been generally accepted that imposing 8 to 12 temperature cycles on electronic hardware is an effective way of driving out defects. This practice has been promoted by MIL-STD-1 540 and the IES Environmental Stress Screening For Electronic Hardware guidelines. As a result, this practice has gained widespread acceptance in the industry as a typical environmental test for electronic hardware. however,

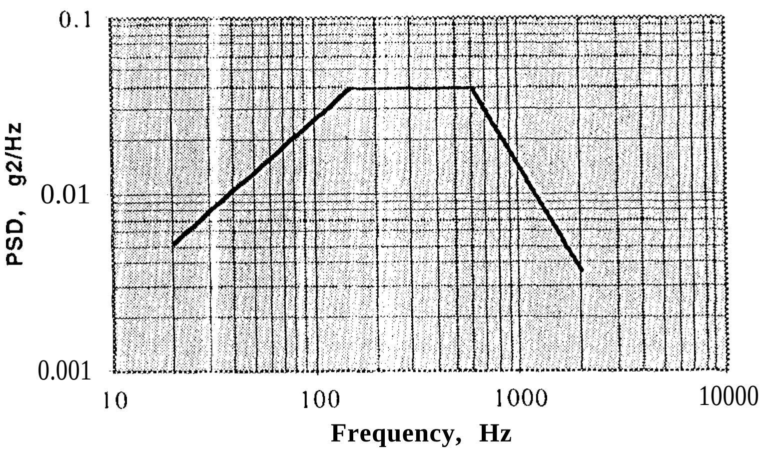

Figure 4- MIL-STD-1 540 Minimum Acceptance Test

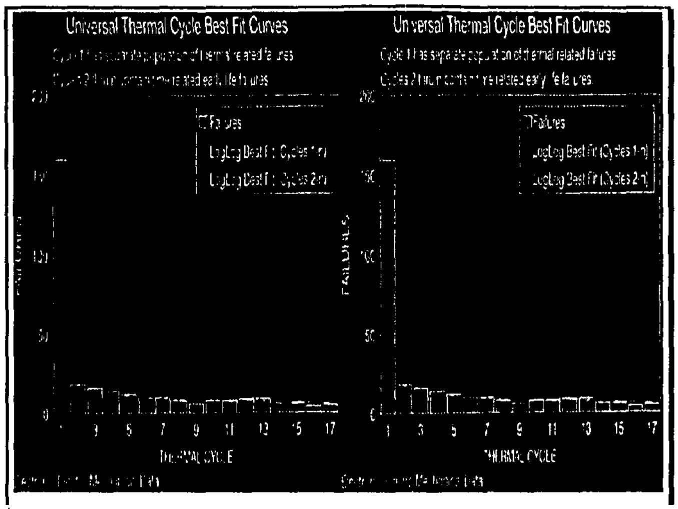

Figure 5- Universal Thermal Cycle Failure Plot

failure data from temperature cycling tests shows that, in reality, this test may not be as effective as thought.

The study examined the failure data from temperature cycling tests. The data shows two distinct failure populations. There is a very high number of failures during the first cycle, followed by a drastically reduced and slowly decreasing number of failures during subsequent cycles. This behavior is shown in Figure 5.

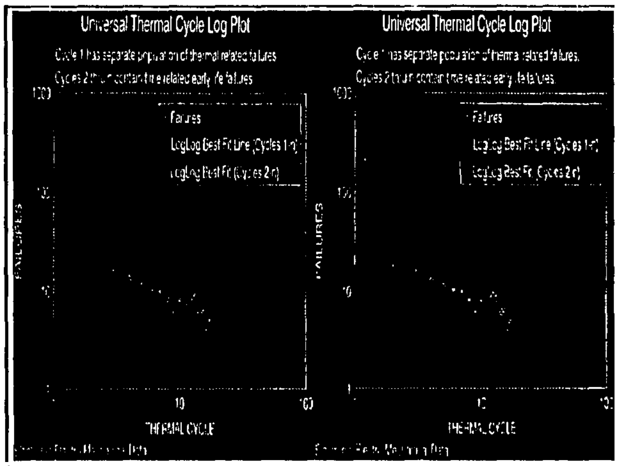

Figure 6- Log-log Thermal Cycle Failure Plot

Figure **6 shows a log-log plot** of the data with best fit curves for cycle 1-n and cycles 2-n. It is clear that the curve tit is much better without the first cycle failure data. This supports the thesis that the failures come from two different populations.

Furthermore, a study of the data presented in the 1981 IES ESSEH guidelines, repeated here in Figure 7, shows that the only set of data corresponding to temperature cycling (without vibration tests between cycles) exhibits similar behavior.

The conclusion of the study is that, based on data from a wide sampling of electronics bardware tests, the first cycle failures are temperature change induced failures, while the failures during subsequent cycles are time dependent, This leads to a further conclusion that, if one is truly seeking the most effective testing sequence, a single cycle test followed by a burn-in at elevated temperature not only can be more effective in driving out defects, but is less costly than multiple temperature cycles. This knowledge can be used to provide a project with alternative ways of testing its electronic assemblies to the same level of effectiveness, while expending less <resources on environmental test equipment utilization. fewe

The subject of temperature cycling versus temperature dwell test effectiveness is the focus of continued discussions, and will bc the subject of an upcoming NASA sponsored workshop,

The ETEA Study

A continuing effort at J}'], has focused on evaluating the effectiveness of various environmental tests. The Environmental Test Effectiveness Analysis (ETEA) program has been sponsored by NASA Code Q Office of Safety and Mission Assurance for the purpose of performing these test effectiveness studies [5]. These assessments have studied issues such as the evaluation of two spacecraft environmental test programs to study the relative effectiveness of thermal vacuum, dynamics, and EMC tests. Other studies have evaluated -the effectiveness of assembly level dynamics testing, ' the effectiveness of the vacuum environment in thermal vacuum tests, correlation of advances in the spacecraft digital technology with EMC test failure rate, as well as many others. The results of these studies are published in reference [6].

These studies help form the basis for future test tailoring decisions, with the ability to identify tests that may be more effective than others, or

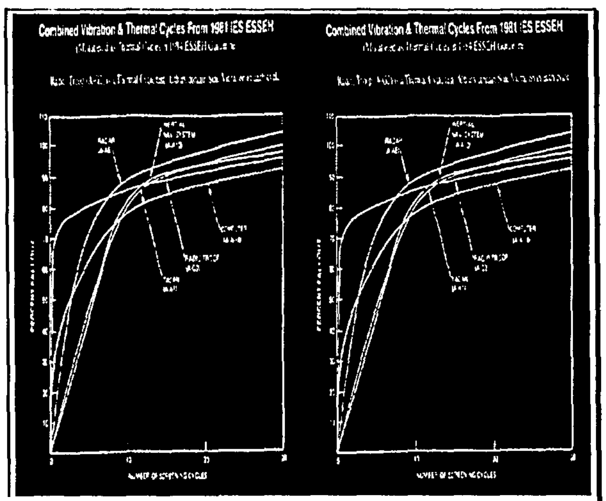

Figure 7- Combined Vibc & Thermal Cycle Data

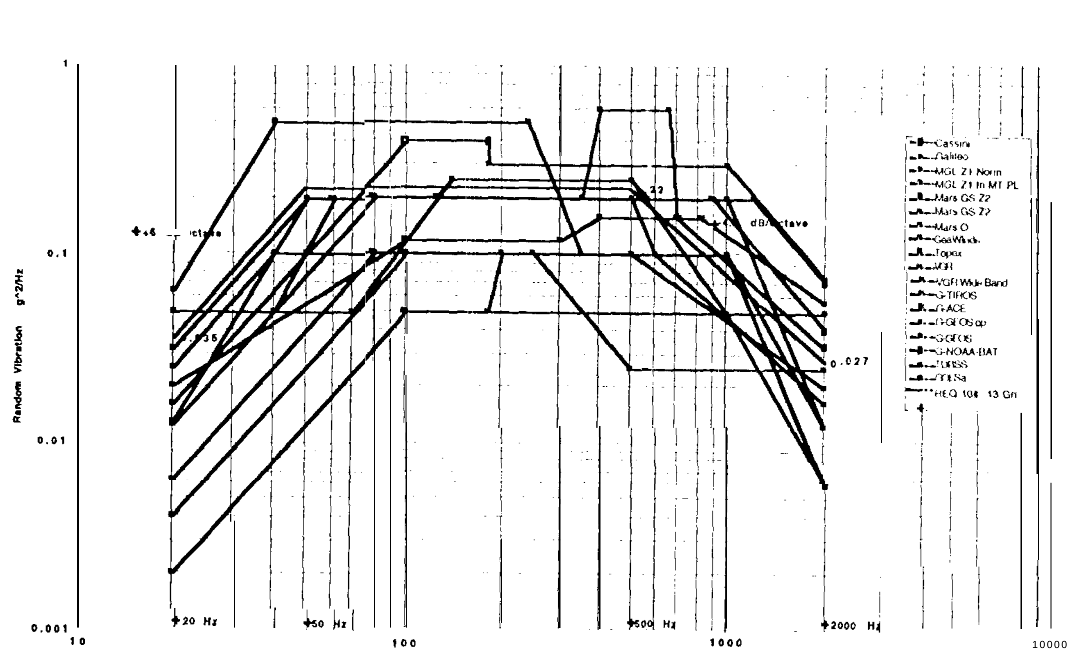

Figure 8-2 Sigma Random Vibration Envelope

adding understanding of the types of anomalies that a given test is particularly useful in uncovering.

For example, one study concluded that on Voyager and Galileo, 52'% and 70%, respectively, of the problems uncovered during dynamics testing required powered on vibration for detection. Oot of these problems, 3 Voyager and 1 on Galileo would have caused major mission problems had they gone undetected. Another study determined that approximately 60% of problems found at assembly level testing are design problems, while parts and workmanship problems constitute 12'% and 28% respectively. These types of results provide insight into the types of problems expected during tests, as well as the types of tests **which are most perceptive.**

Test Program Streamlining Efforts

JPL has initiated a number of efforts to streamline the development of environmental requirements and specifications for flight hardware. Working in conjunction with the Greenbelt, Maryland based Goddard Space Flight Center (GSFC), the Laboratory recently established a set of "2-sigma" generic environmental envelopes, which could eventually allow "off the shelf' hardware to be flown on a number of standard launch vehicles, in a related study, the Accurate, Cost Effective Qualification (ACEQ) program has been developed to correlate system requirements with failure modes, and then assess the effectiveness of test, analysis and process control in identifying these modes. Each of these efforts will be discussed below.

2-Sigma Requirements Envelope

In a recent study, JPL and GSFC attempted to determine ifa set of reasonable test levels could be defined which would bracket 95°/0 of expected flight hardware environments. In this so-called 2s requirements effort, launch environment data was gathered from a variety of U.S. and foreign launch vehicles and previously flown payloads, and appropriately enveloped. Ifa box or subsystem were to be qualified to these envelope levels, then "that box or subsystem could, with 95% probability, fly on any mission using, any launch vehicle or facility in the world.

The study encompassed dynamic, thermal and electromagnetic compatibility requirements. For the dynamic environments, random vibration, acoustic and pyrotechnic shock levels were included.

Figure 8 shows the random vibration envelope which resulted from the effort, based upon flight data for several booster configurations including the Atlas/Centaur, Delta 3000, Delta II, Titan 111, Titan IIIC, Titan34D, Titan/IUS, Scout, Pegasus, Taurus, Proton and Ariane 4.

The same study collected information on the assembly qualification temperatures used on various programs as shown in Figure 9. As can be seen, a qualification temperature range of -20/-+75 °C encompasses missions ranging from earth orbiters to interplanetrary exploration flights.

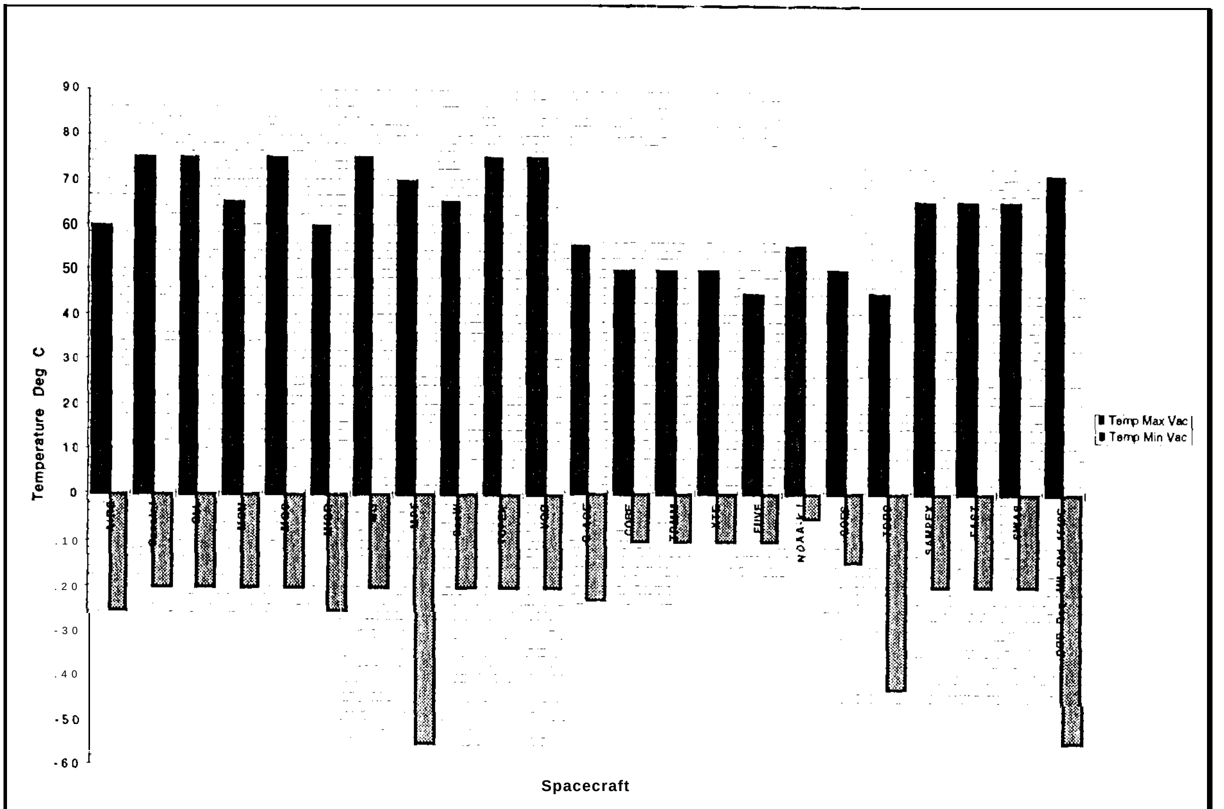

Figure 9-2 Sigma Hardware Qualification Temperatures

As desirable as a 'universal' set of requirements would be, this approach may not be suitable for all better, cheaper, faster missions. **If** these qualification levels are achievable without paying high resource penalties, they are desired, since they bracket so many missions, making a piece of hardware of utility to many flight projects. However, if these levels impose undue penalties in the form of cost, weight, complexity, or schedule, they clearly do not meet the needs of the current trend toward streamlined projects.

<u>Accurate, Cost-Effective Qualification</u>

While the need for tailoring the mission assurance program for the new types of projects was recognized, there has not been a readily available tool or methodology for performing the necessary trade-offs based on the project performance requirements, the failure modes inherent in the technology being used, and the effectiveness of the various test and prevention activities available. The development of the Advanced, Cost Effective Qualification (ACEQ) methodology was pursued to develop such a methodology [6]. This was meant as a means of providing a systematic method to re-engineer, or streamline the qualification process.

The key to this methodology is its attempt to identify the overlap, voids, and redundancies between mission requirements, failure modes, and the available PACTS (preventions, analyses, controls, and tests). It begins by establishing the requirements which will lead to meeting the customers desires. Once a technology is chosen, the failure modes relevant to that technology are identified, and then a matrix is generated which charts the failure modes and the requirements, and the effect of each failure mode on each requirement is assessed and ranked. Critical failure modes have a higher influence coefficient than failure modes with minor effects on the requirements. At this level, one can identify holes or redundancies in the requirements. For example, if there are no failure modes which would affect the ability to meet a given requirement, that requirement is probably not necessary to meet the customer's desires.

Once the relationship between the failure modes and requirements-are established, a test effectiveness matrix can be developed. This matrix lists the failure modes identified above versus the available PACTS, One of the strengths of the ACEQ methodology lies in utilizing a comprehensive 'tool box' approach by listing the preventions, analyses, controls, and tests together to identify their total effect on the failure modes. By combining all these PACTS, one can begin to identify overlap, redundancies, or failings in the qualification program. If several activities identify the same failure mode, the redundancies can be identified and eliminated. Conversely, it may be possible to identify failure modes which are not addressed by any of the traditional activities, and a way of preventing or screening for those failure modes may be investigated. This test effectiveness matrix enables the project to identify the most important assurance activities, and thus provides a tool for effective risk management by enabling the project manager to concentrate their resources on the most effective PACTS.

Conclusions

In a time of shrinking project budgets and schedules, it is often thought that excessive risks are inevitable. However, by pursuing a thorough understanding of the objectives and effectiveness of the various environmental tests, and developing systematic methods for applying that understanding to a project, the diminishing test budget can be put to the most effective use. It will be increasingly important for the environmental test engineer to apply a systems approach to his or her discipline in order to recommend activities which are based on knowledge and understanding, and not just tradition and 'accepted' practice.

Acknowledgments

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